

Probing the Anisotropy of the Milky Way Gaseous Halo-II: sightline toward Mrk509

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ABSTRACT

Hot, million degree gas appears to pervade the Milky way halo, containing a large fraction of the Galactic missing baryons. This circumgalactic medium (CGM) is probed effectively in X-rays, both in absorption and in emission. The CGM also appears to be anisotropic, so we have started a program to determine CGM properties along several sightlines by combining absorption and emission measurements. Here we present the emission measure close to the *Mrk 509* sightline using new *Suzaku* and *XMM-Newton* observations. We also present new analysis and modeling of *Chandra* HETG spectra to constrain the absorption parameters. The emission measure in this sightline is high, $EM = 0.0165 \pm 0.0008 \pm 0.0006 \text{ cm}^{-6} \text{ pc}$, five times larger than the average. The observed O VII column density $N(\text{O VII}) = 2.35 \pm 0.4 \times 10^{16} \text{ cm}^{-2}$, however, is close to the average. We find that the temperature of the emitting and absorbing gas is the same: $\log T(\text{K}) = 6.33 \pm 0.01$ and $\log T(\text{K}) = 6.33 \pm 0.16$ respectively. We fit the observed column density and emission measure with a β -model density profile. The central density is constrained to be between $n_0 = 2.8\text{--}6.0 \times 10^{-4} \text{ cm}^{-3}$ and the core radius of the density profile has a lower limit of 40 kpc. This shows that the hot gas is mostly in the CGM of the galaxy, not in the Galactic disk. Our derived density profile is close to the Maller & Bullock (2004) profile for adiabatic gas in hydrostatic equilibrium with an NFW dark matter potential well. Assuming this density profile, the minimum mass of the hot CGM is $3.2 \times 10^{10} M_{\odot}$.

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1. Introduction

We have known for decades that stellar and ISM components of galaxies, including our own Milky Way, account for only a small fraction of their baryons, compared to the amount expected in their halos from the universal baryon fraction $\Omega_b/\Omega_m = 0.17$ (Sommer-Larsen 2006; Bregman 2007; Anderson & Bregman 2010; Gupta et al. 2012; Miller & Bregman 2013; Miller et al. 2016). As interesting as the missing baryons problem is the missing metals problem; nearby galaxies are also short of metals expected from the star formation history of the universe (Shapley et al. 2003). Perhaps a solution to both of these problems lies in the highly ionized warm-hot gas in the circumgalactic medium (CGM) of galaxies. Recent theoretical models suggest that the CGM of galaxies contains a large reservoir of warm-hot gas accounting for the majority of galactic baryons (Stinson et al. 2012; Fang et al. 2013; Feldmann et al. 2013; Ford et al. 2013; Roca-Fabrega et al. 2016) and according to Peebles et al. (2014), the CGM could account for 40% of metals produced by star forming galaxies. The distribution, spacial extent, and mass of this warm-hot gas provide important constraints to models of galaxy formation and the accretion and feedback mechanisms.

Although theoretical models predict the existence of the warm-hot gas in the CGM, detecting and characterizing the diffuse CGM has been difficult. Because of our special vantage point, our own Milky Way provides a unique opportunity to probe the CGM of a spiral galaxy. The warm-hot CGM gas can be effectively probed by highly ionized metals; the dominant transitions from such ions lie in the soft X-ray band. In literature there are multiple reports on detection of redshift zero absorption lines due to O VII and O VIII (Nicastrro et al. 2002; Wang et al. 2005; Williams et al. 2005; Fang et al. 2006; Bregman 2007; Miller & Bregman 2013; Fang et al. 2015). But it is difficult to measure the extent, density, and mass of this warm hot gas because of the inherent difficulty in using absorption line studies alone. While the absorption line column density is a product of density and pathlength, emission measure is a product of density square and pathlength, so a combination of absorption and emission studies are required to break the degeneracy and so fully characterize the warm-hot CGM. Indeed various broad-band X-ray observations have revealed an extensive diffuse soft (≤ 1 keV) X-ray background (SXRb). Shadow observations show that there is a significant contribution from the Galactic halo to SXRb (Snowden et al. 2000; Smith et al. 2007; Galeazzi et al. 2007; Henley et al. 2007; Henley & Shelton 2008; Gupta et al. 2009).

In Gupta et al. (2012, hereafter Paper-I), combining *Chandra* observations of O VII and O VIII absorption lines and *XMM-Newton* and *Suzaku* measurements of the Galactic halo emission measure, we found that there is a huge reservoir of ionized gas around the Milky Way, with a mass of over 60 billion solar masses and a radius of over 100 kpc. Thus there appears to be more baryonic mass in the warm-hot CGM than in the entire disk of the

Galaxy and as much mass in metals as in all the stars in the disk. In Paper-I we compared absorption and emission values average over the whole sky. However, shadow observations and other studies of soft X-ray diffuse background show that the emission measure of the Galactic halo varies by an order of magnitude in different sight-lines (Henley et al. 2010; Gupta et al. 2009). Therefore it is crucial to determine the emission measure of emitting gas near absorption sight-lines to understand the differences in physical properties of the CGM across the sky.

In Gupta et al. (2014, hereafter Paper-II) we compared absorption and emission along two sightlines: toward Mrk421 and PKS2155-304. In these two sightlines, the observed column densities are similar, but observed emission measures are different, so their densities and/or pathlengths must be different. Indeed we found that toward Mrk421 and PKS2155-304 the densities are $1.6^{+2.6}_{-0.8} \times 10^{-4} \text{ cm}^{-3}$ and $3.6^{+4.5}_{-1.8} \times 10^{-4} \text{ cm}^{-3}$ and pathlengths are $334^{+685}_{-274} \text{ kpc}$ and $109^{+200}_{-82} \text{ kpc}$ respectively. While the errors on the derived parameters are large, this provides a suggestive evidence that the warm-hot gas in the CGM of the Milky Way is not distributed uniformly.

Here we expand on our previous work and constrain the physical properties (temperature, path-length, density, and mass) of CGM in the sightline toward *Mrk 509*. In sections 2 and 3 we present a detailed analysis of our *XMM-Newton* and *Suzaku* (PI: Gupta) new observations of a blank sky field near *Mrk 509*. We also present detailed reanalysis of the *Chandra* High Energy Transmission Grating (HETG) 2012 observation of *Mrk 509*. Kaastra et al. (2014) have analyzed and modeled the intrinsic absorbers of *Mrk 509*. Here we focus on the redshift zero absorption lines. In section 5 we present results with a uniform density model as well as a β -model. The discussion is presented in §7.

2. Observation and data reduction

A blank X-ray sky field (*Off-field2*) adjacent to *Mrk 509* was observed by *XMM-Newton* and *Suzaku*. The observation IDs, dates, pointing directions and exposure times are summarized in Table 1. Figure 1 shows the ROSAT All Sky Survey (RASS; 0.1-2.4 keV) image in the vicinity of *Mrk 509*, along with the *XMM-Newton* and *Suzaku* pointing of *Off-field2*. *Mrk 509* was observed with *Chandra* Low Energy Transmission Grating (LETG) and High Energy Transmission Grating (HETG) in December 2009 and September 2012 respectively. We presented our results on the $z = 0$ O VII and O VIII absorption lines from the LETG observation in Paper-I. In the following we report on the data reduction of *XMM-Newton* and *Suzaku* observations of *Off-field2* and *Chandra* HETG observation of Mrk 509.

2.1. XMM-Newton observations

Off-field2 was observed by XMM-Newton for 60 ks on November 2013. The observation was performed with the thin filter using the full-frame (FF) mode for all the EPIC (European Photon Imaging Camera) cameras. In this work we used data from the EPIC-pn and EPIC-MOS detectors.

We reduced the data using the XMM-Newton Extended Source Analysis Software¹ (XMM-ESAS; Snowden & Kuntz 2013) as distributed with version 13.5.0 of the Science Analysis System (SAS). We first used the standard SAS *emchain* and *epchain* scripts to produce calibrated events lists from MOS and pn cameras respectively, and then run the XMM-ESAS *mos-filter* and *pn-filter* scripts. **These scripts call the SAS task *espfilt* for light-curve cleaning. It uses broad-band (2.5–8.5 keV) count rate to filter flares.** This process mostly removed the soft proton contamination, but there could be some residual emission left. The resultant good exposure time after this filtering are 45.6 ks, 47.6 ks, and 34.2 ks for the MOS1, MOS2 and pn cameras, respectively. Note that the resulting pn exposures are shorter than the corresponding MOS exposures. As reported in ESAS cookbook, this is likely due to the greater sensitivity of the pn detector, meaning that relatively smaller departures from the mean count rate are flagged as soft proton flares.

Since we are interested in the diffuse emission, we need to remove any contribution to emission from point sources in the field. We detected the point sources and created the source list using the XMM-ESAS task *cheese*. The *cheese* task combines both MOS and pn data for source detection creating images and exposure maps in a selected single band (0.5–2.0 keV). We have selected PSF threshold parameter of *scale=0.2* which corresponds to point source removal down to a level where the surface brightness of a point source is 20% of the surrounding background. We set the detection limit (flux in the energy band of 0.5–2.0 KeV) of 1×10^{-15} erg cm⁻² s⁻¹ to create masks in order to remove the point sources. After removal of bad pixels and point sources, the active fields of view are 5.0×10^{-5} sr and 4.8×10^{-5} sr for the MOS2 and pn respectively.

We used the XMM-ESAS scripts *pn-spectra* and *mos-spectra* to extract spectra from the active fields of view. The spectral extraction scripts also calculated the redistribution matrix file (RMF) and the ancillary response file (ARF) for each spectrum, using the SAS *rmfgen* and *arfgen* tools, respectively. We run the scripts *mos_back* and *pn_back* to calculate corresponding quiescent particle background (QPB) spectra. The QPB spectra were calculated from a database of filter-wheel-closed data, scaled to our observations using data from the

¹<ftp://xmm.esac.esa.int/pub/xmm-esas/xmm-esas.pdf>

unexposed regions of the cameras (Kuntz & Snowden 2008). Before our spectral analysis, we grouped each spectrum such that there are at least 50 counts per bin, and subtracted the corresponding QPB spectrum (Fig. 2).

2.2. Suzaku observations

Off-field2 was also observed with *Suzaku* for 61 ks on May 2012. The data reduction and analysis were carried out with HEASoft version 6.16 and XSPEC 12.8.2 with AtomDB ver.2.0.2. In this work, we analyzed only the X-ray Imaging Spectrometer (XIS1) data, as this has the greatest sensitivity at low energies. We combined the data taken in the 3×3 and 5×5 observation mode using the ftool *xis5 × 5to3 × 3*. We first converted 5×5 mode data to 3×3 mode data and then merged both files with the help of ftool *ftmerge*. Along with standard data processing (e.g. $\text{ELV} > 5$ and $\text{DYE ELV} > 20$), we expanded data screening with the cut-off-rigidity (COR) of the Earth’s magnetic field, which varies as *Suzaku* traverses its orbit. During times with larger COR values, fewer particles are able to penetrate the satellite and the XIS detectors. We excluded times when the COR was less than 8 GV, which is greater than the default value (COR 4 GV), as lowest possible background is desired.

Due to *Suzaku*’s broad point spread function (half-power diameter $\sim 2'$ (Mitsuda et al. 2007)), it is hard to detect point sources. Therefore we used the location of point sources determined in the XMM-Newton observation and excluded a region of $2'$ radius around the source location.

We run ftool *xisrmfgen* and *xissimarfgen* to produce the RMFs and ARFs. For the ARF calculations we assumed a uniform source of radius $20''$ and used a detector mask which removed the bad pixel regions. We extracted the spectra of non-X-ray background from a database of the night Earth data with ftool *xisnxbgen*.

2.3. Chandra Observations

Mrk 509 was observed by *Chandra* HETG in 2012 for a total of 280 ks (ObsID: 13864 & 13865). The HETG is comprised of two gratings: the medium energy gratings (MEG) and the high energy gratings (HEG), which disperse spectra into positive and negative spectral orders. Since we are interested in oxygen absorption lines we used the data from MEG only and reduced it using the standard Chandra Interactive Analysis of Observations (CIAO) software (v4.6) and Chandra Calibration Database (CALDB, v4.6.3) and followed the stan-

dard Chandra data reduction threads². First we run the *mkgrmf* CIAO script to create the first order positive and negative MEG RMFs, needed for spectral analysis of grating observations. Further, to increase the S/N we co-added the negative and positive first-order spectra with *add_grating_orders* and built the ARFs using the *fullgarf* CIAO script.

3. Spectral Analysis: Emission

We used Xspec for spectral analysis of *XMM-Newton* and *Suzaku* data. We used the χ^2 statistics as a goodness-of-fit measure and all errors are given at the 1σ confidence level. The goal of our *XMM-Newton* and *Suzaku* observations of *Off-field2* is to measure the contribution of galactic halo emission to the soft diffuse X-ray background (SDXB) near *Mrk 509*. SDXB spectra have three distinct components: (1) a foreground component consisting of solar wind charge exchange (SWCX) and the local bubble (LB); this is modeled as an unabsorbed plasma with thermal emission in collisional ionization equilibrium (CIE); (2) a background component made of unresolved extragalactic sources; this is modeled with an absorbed power law; and (3) Galactic halo emission; this is modeled as an equilibrium thermal plasma component absorbed by the gas in the Galactic disk.

Both the Galactic halo and foreground components (SWCX+LB) have similar spectral shape, primarily X-ray lines from highly ionized metals, mostly O VII and O VIII. As a result, disentangling the two is very difficult. To minimize the SWCX contribution, which varies both in spectral composition and flux on scales of hours to days, we use proton flux filtering (Smith et al. 2007; Yoshino et al. 2009). We obtained the solar wind proton flux data from OMNIWeb³. Figure 3 shows the solar wind proton flux during *XMM-Newton* and *Suzaku* observations of *Off-field2*. During the *Suzaku* observation, solar wind proton flux is much higher than during the *XMM-Newton* observation. We investigated the effect of the higher proton flux during *Suzaku* observation by comparing surface brightness of O VII $K\alpha$ and O VIII $K\alpha$ lines in *XMM-Newton* and *Suzaku* spectra. As expected, O VII $K\alpha$ line intensity is higher by about a factor of 1.5 during the *Suzaku* observation compared to the *XMM-Newton* observation (Table 2), implying that the *Suzaku* spectra have significant contamination from SWCX. Thus for further analysis we use only the *XMM-Newton* spectrum of *Off-field2*.

²<http://cxc.harvard.edu/ciao/threads/index.html>

³<http://omniweb.gsfc.nasa.gov/>

3.1. Spectral Modeling: Emission

We **simultaneously** fit the *XMM-Newton* MOS1 and MOS2 filtered diffuse background spectra with the three component model noted above. Even after the data cleaning described in §2.1, there may remain some residual soft proton contamination (Snowden & Kuntz 2011). This is modeled as an additional powerlaw that was not folded through the instrumental response. We also modeled the instrumental Al and Si fluorescence lines at 1.49 and 1.74 keV respectively, with two gaussians.

We use the *APEC* model with plasma temperature of $T = 1.2 \times 10^6$ K (frozen) and emission measure (EM) of $0.0032 \text{ cm}^{-6} \text{ pc}$ (frozen) for the foreground component (SWCX plus LB). We determined the normalization/EM of the foreground component using data from Snowden et al. (2000) catalog of SXR shadows as described in detail in Paper-II. We find 5 shadows in the catalog closest to our sightline with average foreground R12 count-rate of $337 \times 10^{-6} \text{ counts s}^{-1} \text{ arcmin}^{-2}$ corresponding to EM of $0.0032 \text{ cm}^{-6} \text{ pc}$.

The contribution from unresolved extragalactic sources is modeled with an absorbed power-law. The Galactic column density was fixed to $N_H = 4 \times 10^{20} \text{ cm}^{-2}$ (Dickey & Lockman 1990), and power-law slope and normalization were left as free parameters in the spectral fit.

Finally we determine the hotter Galactic halo contribution, modeled as an equilibrium thermal plasma component absorbed by the gas in the galactic disk (Fig. 4). We measured the galactic halo temperature of $\log T(\text{K}) = 6.33 \pm 0.01$ and emission measure of $0.0165 \pm 0.0008 \pm 0.0006 \text{ cm}^{-6} \text{ pc}$. The first error indicates the statistical error, and the second error indicates the estimated systematic error due to our assumed foreground spectra (for details see Paper-II). The EM towards *Mrk 509* is unusually high, about five times the sky average of $0.0030 \pm 0.0006 \text{ cm}^{-6} \text{ pc}$. Henley et al. (2007) have reported such high Galactic halo EM towards a filament in the southern Galactic hemisphere.

XMM-Newton pn spectrum is consistent with the MOS model ($\chi^2_\mu = 1.2$), though there are some residuals at energies 0.4–0.7 keV. This might be due to under- or over-estimation of the pn particle background as discussed at Snowden & Kuntz (2013). Thus for further calculations we use only the MOS2 spectrum fit results (Henley et al. (2010) have also used only the MOS data for galactic halo emission measurements).

4. Spectral Analysis: Absorption

For the spectral analysis of absorption along the sightline to Mrk 509, we binned the *Chandra* MEG spectra to 0.01Å and analyzed using the CIAO fitting package *Sherpa*.

Since we are interested in $z = 0$ highly ionized metal lines we fit the continuum spectrum in the 15 – 23 Å range with a powerlaw, absorbed by the Galactic column density. *Mrk 509* is known to have intrinsic absorption (Kaastra et al. 2014 and references there in), so we fit the intrinsic absorbers of *Mrk 509* with multiple gaussians.

After fitting the continuum and intrinsic features, the $z = 0$ O VII K α , O VII K β and O VIII K α absorption lines are detected with more than 3σ significance (Fig. 5). We fit these lines with narrow Gaussian features of line width 1 mÅ. The best-fit line parameters and errors (calculated using the projection command in *Sherpa*) are given in Table 3 and the spectrum is shown in figure 5. The measured equivalent widths (EWs) are consistent within 1σ error of our previous measurements (Paper-I) done with the *Chandra* LETG 2009 observation.

The O VII K α absorption line is clearly saturated in the *Mrk 509* data. The measured $\frac{EW(K\beta)}{EW(K\alpha)}$ ratio is 0.56, much higher than the expected ratio of 0.156 for optically thin O VII lines. For the saturated lines like we observe here, converting the observed EWs to column densities is non-trivial. We used the method described in detail at Paper-I to obtain constraints on the O VII column density: $\log N_{OVII} (cm^{-2}) = 16.6 \pm 0.4$ and the velocity dispersion parameter $b = 70\text{--}200 \text{ km s}^{-1}$. The measurement uncertainties are large due to the weak O VII K β line, but we can do better by using the code PHASE, as discussed below.

4.1. Fitting with PHASE

Our hybrid photo- and collisional-ionization code PHASE (Krongold et al. 2003) automatically takes into account line saturation by using Voigt profiles to fit absorption lines. Additional advantage of using the code is that it fits the entire 11.0 to 23 Å spectrum, taking into account lines which are not individually detected, providing better constraints. The fit provides constraints on the column density, velocity dispersion parameter and temperature of the absorbing plasma. Best fit PHASE parameters are reported in Table 4 and the spectrum is shown in figure 6. The O VII column density was found to be $\log N_{OVII} (cm^{-2}) = 16.37^{+0.07}_{-0.08}$, somewhat lower than, but consistent with that noted above, and with much smaller errors.

In the Mrk 509 spectrum we could determine the $z = 0$ Ne IX column density accurately ($\log N_{NeIX} (cm^{-2}) = 15.85 \pm 0.2$) even though the line was not individually detected.

The velocity dispersion parameter obtained with PHASE fitting is $b = 74_{-74}^{+80}$ km s⁻¹ (where the lower limit is pegged at the hard limit) and temperature $\log(T/k) = 6.33 \pm 0.16$. The b -parameter is not well constrained, but is consistent with the value obtained from using the $K\alpha$ and $K\beta$ line ratio noted above. We could not constrain the metallicity of the gas independently in PHASE; assuming $Z = 0.3Z_{\odot}$, the fit gives total equivalent Hydrogen column density of $N_H = 2.15 \times 10^{20}$ cm⁻² (Table 4).

5. Results

While the strength of an absorption line depends on the ionic column density of the intervening gas ($N_H = \mu n_e R$, where n_e is the electron density and R is the path-length, and μ is the mean molecular weight), the emission is sensitive to the square of the number density ($EM = n_e^2 R$, assuming a constant density plasma). Therefore a combination of absorption and emission measurements breaks the degeneracy and provides constraints on physical properties such as path-length and density of the absorbing/emitting gas.

From the PHASE model of z=0 absorption lines and galactic halo emission model, we constrained the temperature of the absorbing and emitting gas to $\log(T(K)) = 6.33 \pm 0.16$ and $\log(T(K)) = 6.33 \pm 0.01$ respectively. Since the temperature of the absorbing and emitting gas is the same, it is reasonable to assume that both absorption and emission arise in the same plasma. We can now combine the column density and emission measure to extract physical properties of the absorbing-emitting warm-hot gas.

5.1. Uniform Density Halo Model

Assuming that absorbing/emitting plasma has a constant density we derive the density of:

$$n_e = (6.6_{-1.2}^{+1.7}) \times 10^{-4} \left(\frac{0.5}{f_{OVII}} \right)^{-1} \text{cm}^{-3} \quad (1)$$

and the path length of:

$$R = (126_{-41}^{+43}) \left(\frac{8.51 \times 10^{-4}}{(A_O/A_H)} \right) \left(\frac{0.5}{f_{OVII}} \right)^2 \left(\frac{0.3Z_{\odot}}{Z} \right) \text{kpc} \quad (2)$$

where the Solar Oxygen abundance of $A_O/A_H = 8.51 \times 10^{-4}$ is from Anders & Ebihara

(1989) and f_{OVII} is the ionization fraction of O VII. Simulations of the CGM around disk galaxies (Sommer-Larsen 2006; Toft et al. 2002) suggest the mean metallicity of gas is $Z = 0.2 \pm 0.1 Z_{\odot}$. These values of metallicities are also consistent with observational results for the outskirts of groups (Rasmussen et al. 2009), clusters of galaxies (Tamura et al. 2004) and external galaxies (Anderson et al. 2016; Bogdan et al. 2013a). As path length is inversely proportional to the metallicity (equation 2), lower values of metallicity corresponds to larger path-length and consequently the higher mass. Thus to be conservative, and consistent with our Paper-I and Paper-II, we used $Z = 0.3 Z_{\odot}$.

The CGM parameters along just one sightline are presented here, and as noted in §1 the Milky Way CGM is likely anisotropic. So we cannot determine the CGM mass using parameters of only one sightline. Nonetheless, for the sake of comparison with another density distribution such as the β -model discussed below, we will assume spherical symmetry and covering fraction of 1 of the warm-hot CGM gas with density and pathlength calculated above. This leads to the mass of the plasma = $5.4 \times 10^{10} M_{\odot}$. For a covering factor of 0.72 used in Paper-I, the mass is = $3.9 \times 10^{10} M_{\odot}$. This is lower than the mass derived in Paper-I (= $2.3 \times 10^{11} M_{\odot}$); this is largely due to the unusually high EM along this sightline, which leads to larger density and smaller pathlength (§7).

5.2. β -model

Above (and also in Paper-I and Paper-II) we had assumed a constant density plasma, but the Galactic halo likely has a non-uniform density profile. Since the EM is biased toward high density, this could affect the results. A realistic halo is likely to have some density profile that falls with radius, so we should use a model with a reasonable density distribution and compare the model predictions to observations for obtaining constraints on the structure of the Galactic CGM.

The distribution of the warm-hot gas around several elliptical galaxies follows a beta-model profile in which the density is high in the center and falls off with radius (Forbes et al. 2012; Mathur et al. 2008); gas in clusters and groups of galaxies also follows similar profile (Jones & Forman 1984; Forman et al. 1985; Mulchaey & Zabludoff 1998). Anderson & Bregman (2011), Anderson et al. (2016) and Dai et al. (2012) used the β model to fit the radial surface brightness profile of hot halo gas around spiral galaxies.

The β -model is given by

$$n(r) = n_0 [1 + (r/r_c)^2]^{-3\beta/2}$$

where r is the galactocentric radius, n_o is the central density, r_c is the core radius and β describes the shape. We have two measurements (column density and emission measure) and three unknowns (n_o , r_c and β), so the parameters are degenerate. We first assumed $\beta=0.5$ in our calculations and then varied the value of β to see its effect on the results.

Our sightline to *Mrk 509* passes through the Milky Way halo along the direction fixed by the Galactic coordinates ($l = 35.97^\circ$, $b = -29.85^\circ$), and our measurements of absorption and emission are along this sightline. So we first converted $n(r)$ to $n(s)$ where s is the pathlength along the sightline. We assumed that we are at 8 kpc from the Galactic center and the virial radius of the Galaxy is 250 kpc, providing the maximum pathlength for integration. Using *Mathematica*, we then determined the values of n_o and r_c which are consistent with both the absorption column density (N_H) and the emission measure (EM).

The results are shown in figure 7, where n_o/μ is plotted on the X-axis and r_c on the Y-axis. Solid lines mark the best-fit and error contours for the observed column density and the dash lines are the same for the emission measure. The central density is constrained to be between $n_o = 2.8\text{--}6.0 \times 10^{-4} \text{ cm}^{-3}$. For the core radius, however, we only have a lower limit $r_c \geq 40$ kpc. For larger values of β , the lower limit on r_c increases ($r_c \geq 50$ kpc for $\beta = 0.6$), the upper limit on n_o becomes slightly smaller ($n_o = 5.8 \times 10^{-4} \text{ cm}^{-3}$ for $\beta = 0.6$), but the lower limit on n_o remains the same.

For $r_c = 40$ kpc (lower limit) and the corresponding $n_o = 0.0006 \text{ cm}^{-3}$, the mass within the virial radius of 250 kpc is $3.2 \times 10^{10} M_\odot$. For the lower limit of density ($n_o = 0.00028 \text{ cm}^{-3}$) and the corresponding $r_c = 280$ kpc, the mass is $9.98 \times 10^{10} M_\odot$ (Table 5).

6. Comparison with External Galaxies

Similar to the Milky Way, other spiral galaxies should also have massive, extended reservoirs of ionized hot gas in the CGM. X-ray absorption line spectroscopy of galactic haloes is difficult because only a small number of AGNs are bright enough, but several authors have studied the halos around spiral galaxies in emission. Most of these, however, are massive spiral galaxies, not Milky way-type.

Anderson et al. (2016) and Dai et al. (2012) detected hot gaseous halos in emission around the giant spiral galaxies NGC 1961 and UGC 12591, extending to 40-50 and 110 kpc respectively. These authors estimates the mass of their hot halo gas to be $5 \times 10^9 M_\odot$ and $3.9 \times 10^9 M_\odot$ respectively within a radius of 50 kpc, and when density profiles are extrapolated to virial radii of 500 kpc, the implied hot halo mass is $1\text{--}3 \times 10^{11} M_\odot$. Similarly Bogdan et al. (2013a,b) have detected X-ray emission around two other spiral galaxies NGC 6753 and

NGC 266 and estimated the hot X-ray gas mass within ~ 60 kpc to be $1.2 \times 10^{10} M_\odot$ and $9.1 \times 10^9 M_\odot$, respectively. Though the detected masses in hot halos of these galaxies are significant, it is not a major contributor to the galactic missing baryons because these are very massive galaxies; it falls short by an order of magnitude.

Around low mass (Milky Way type) spiral galaxies, the picture is a bit different. Strickland et al. (2004) using *Chandra* observations found diffuse X-ray emitting halos in eight nearby ($D < 17$ Mpc) galaxies extending to radii of 18 kpc. Since these are very nearby galaxies, the *Chandra* field of view probes only a 20 kpc region around the galaxies. With *Suzaku* observation, Yamasaki et al. (2009) confirmed the X-ray halo of NGC 4631 ($D \sim 8$ Mpc) extending out to about 10 kpc from the galactic disk. With *XMM-Newton*, Tullmann et al. (2006) detect the diffuse gaseous X-ray halos extended over a range of 4–10 kpc around nine nearby star-forming edge-on spiral galaxies. But these observations (8 – 55 ks) are not deep enough to detect soft X-ray halos extending out to large radii.

Recently Bogdan et al. (2015) searched for the hot coronae around lower mass spiral galaxies with stellar masses of $(0.7 - 2.0) \times 10^{11} M_\odot$ using *Chandra* ACIS observations. They did not detect a statistically significant hot corona around any of their sample galaxies. The authors noted that the low effective area of *Chandra* ACIS-I or smaller field-of-view of ACIS-S might be reasons for the non-detections.

So we see that the observations of Milky Way-type galaxies were either too shallow or with too small a field of view to detect extended, massive CGMs. Extended, massive CGMs are detected around massive spiral galaxies, but they do not contribute significantly to the baryon budget. Why some spiral galaxies have a large fraction of baryons in their CGM and some do not? The extent of the CGM in a galaxy and the fraction of missing baryons it contains may depend on several properties of a galaxy: stellar mass (Bogdan et al. 2015), specific star formation rate (Tumlinson et al. 2011), or dark matter halo mass (Oppenheimer et al. 2016). All the three reasons could be related as galaxies with higher mass have substantially lower specific star formation rates (Genel et al. 2014; Damen et al. 2009) and feedback may affect both the star formation rate and stellar mass. Radio-mode feedback may expel gas from a galaxy leading to both smaller stellar mass and less massive CGM (Bogdan et al. 2015). In the simulations of Roca-Fabrega et al. (2016), the fraction of hot gas mass in more massive galaxies is indeed smaller.

7. Discussion

In Paper I we had assumed a constant density model to determine the CGM parameters of the Milky Way. We found a huge reservoir of baryonic mass of over $6 \times 10^{10} M_{\odot}$. This result was criticized by some who argued that the mass is overestimated because of the assumption of constant density (Wang & Yao 2012, also see Mathur 2012 and references therein). In Paper II we made logical arguments and showed mathematically that that is not the case. On the contrary, any non-uniform density profile with density falling with radius would necessarily lead to larger mass estimates. Here we confirm our arguments by comparing the constant density model with a β -model. Even the lower limit on mass is comparable to that with a constant density (see Table 5), and is over twice as much for the lower limit on the central density.

CGMs also likely have a radial temperature profile, but we do not have observational constraints to determine the temperature profile, so we assume constant temperature. With more sightlines we will have more observables to determine the temperature profile. We note that Faerman et al. (2016) also assume that the mean gas temperature is constant as a function of radius in their theoretical model.

Another matter of contention in literature is the location of the warm-hot gas, whether in the ISM of the Galactic disk, the CGM, or beyond. In Paper-II we had argued that the Galactic ISM cannot be the major contributor to the $z = 0$ absorption lines. Here we constrain the core radius of the absorbing/emitting gas to be over 40 kpc, clearly ruling out the ISM origin and placing the gas in the CGM of the Galaxy (see also Nicastro et al. 2016a).

In Paper-I we had used sky-average values of column density and emission measure, with $\log N_{OVII} (\text{cm}^{-2}) = 16.19^{+0.08}_{-0.08}$, and $EM = 0.003 \text{ cm}^{-6} \text{ pc}$. What we find here, along the *Mrk 509* sightline is $\log N_{OVII} (\text{cm}^{-2}) = 16.37^{+0.07}_{-0.08}$, and $EM = 0.0165 \pm 0.0008 \pm 0.0006 \text{ cm}^{-6} \text{ pc}$. Thus, along the *Mrk 509* sightline the O VII column density is larger by 0.2 dex and the emission measure is larger by a factor of 5. As a result, the density along this sightline is larger than average and the pathlength smaller than average (for a constant density model as in Paper-I). The parameters along the two sightlines presented in Paper-II are: $\log N_{OVII} (\text{cm}^{-2}) = 16.22 \pm 0.23$ & 16.09 ± 0.19 , and $EM = 0.0025 \pm 0.0003 \pm 0.0005 \text{ cm}^{-6} \text{ pc}$ & $0.0042 \pm 0.0003 \pm 0.0007 \text{ cm}^{-6} \text{ pc}$, respectively. This underscores the value of measuring absorption and emission along the same sightline to derive the physical properties of the warm-hot gas. We should do so for several sightlines through the MW-CGM to understand its average properties and anisotropy. Part of the anisotropy would arise from our location in the Galaxy as different sightlines would probe different parts of the Galactic CGM (Nicastro et al. 2016b, and references therein). But part of the anisotropy could also be intrinsic, as suggested

by simulations of Roca-Fabrega et al. (2016). We will investigate this further with more sightlines with absorption and emission observations.

In figure 8 we have plotted the β –model profile in the *Mrk 509* direction together with the profile obtained by Fang et al. (2013), which is the Maller & Bullock (2004) profile. The Maller & Bullock profile specifies the density and temperature profiles for adiabatic hot gas with polytropic index $n = 5/3$ in hydrostatic equilibrium in an NFW dark matter potential well. We see that shape of their profile is similar to our β –model profile for the lower limit of r_c , although our density is higher. Our lower limit on the central density is similar to theirs, but our corresponding profile is flatter. Given that the β –model we present here is deduced from only one sightline, and that too with unusually high emission measure, the differences are not surprising.

Recently Faerman et al. (2016) presented an analytic phenomenological model for warm-hot CGMs of L^* galaxies. The hot gas is in hydrostatic equilibrium in a Milky Way gravitational potential. They find the median temperature of the hot gas to be 1.8×10^6 K, similar to what we find for the MW CGM. They also find the CGM to be extended, slightly beyond the virial radius, and massive with $1.35 \times 10^{11} M_\odot$, accounting for missing baryons in galaxies in the local universe. These results, as well as those from Fang et al. (2013) and other theoretical models noted in §1, provide strong support for our results on the Milky Way CGM.

In these works the density distribution of the warm-hot gas is presented as a smooth profile. It is possible, however, that the gas is clumpy and this could have a noticeable impact on model fits because emission measures scale with n^2 while absorption scales with n . Recent theoretical simulations by Roca-Fabrega et al. (2016) show the presence of filamentary structure in the CGM. In future work when we have emission and absorption measurements along several directions, we will include clumping factors $\langle n^2 \rangle / \langle n \rangle^2$ in our models to assess their impact on our interpretation, and we will look at hydrodynamic simulations of galaxy formation for guidance about expected levels of clumping and anisotropy. We note, however, that in contrast to the cool CGM component traced by high-velocity HI clouds, we expect the hot gas component detectable in X-ray data to be relatively smooth (e.g., Stocke et al. 2013). Faerman et al. (2016) include clumping in their models, but the higher density clumped gas is cooler, traced by O VI and the hotter gas, probed by O VII and O VIII is indeed smooth.

To conclude, the hot gaseous CGM of the Milky Way appears to be diffuse and extended. The CGM is clearly anisotropic as shown by the distributions of both absorption and emission measurements. We have determined the properties of the hot CGM by combining absorption and emission measurements along three sightlines, two of which were presented in Paper-II and one is presented in this paper. Additionally in this paper we have fitted the absorption

spectrum with a theoretical collisional-ionization model, obtaining tight constraints on the temperature of the gas. We have also added a β -model density profile and show that the CGM remains diffuse, extended and massive. Our results are consistent with numerical simulations as well as analytic models and suggest that a large fraction of the MW missing baryons reside in its hot CGM.

8. Acknowledgments

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Table 1: Summary of observations for *Off-field2* and *Mrk 509*

Experiment	Target	OBSID	Start Date	Exposure (ks)	<i>l</i> <i>deg</i>	<i>b</i> <i>deg</i>
XMM-Newton	<i>Off-field2</i>	722310201	11/19/2013	63	37.4	-30.6
Suzaku	<i>Off-field2</i>	509043010	05/07/2014	61	37.4	-30.6
Chandra	<i>Mrk 509</i>	13864	09/04/2012	170	35.9	-29.8
	<i>Mrk 509</i>	13865	09/07/2012	99	35.9	-29.8

Table 2: O_{VII} and O_{VIII} emission lines intensities

Dataset	O_{VII}	O_{VIII}
	$ph\ s^{-1}\ cm^{-2}\ Sr^{-1}$	$ph\ s^{-1}\ cm^{-2}\ Sr^{-1}$
XMM-Newton	19.8 ± 0.4	8.1 ± 0.8
Suzaku	30.9 ± 6.6	7.8 ± 1.5

Table 3. Z=0 Absorption lines observed in the Mrk509 *Chandra* HETG-MEG spectra.

λ_{obs} $m\text{\AA}$	EW $m\text{\AA}$	EW ^a $m\text{\AA}$	Ion Name	λ_{rest} \AA
21.61 ± 0.01	19.5 ± 4.8	23.9 ± 5.0	O VII α	21.602
18.62 ± 0.01	11.0 ± 4.0	11.7 ± 4.1	O VII β	18.627
18.97 ± 0.01	12.0 ± 3.4	10.3 ± 4.3	O VIII α	18.969

^aMrk509 Chandra LETG measurement

Table 4. Best fit PHASE parameters

Parameter	z=0 Component
$\log T(K)$	6.33 ± 0.16
$\log N_H (cm^{-2})$	20.33 ± 0.19^a
$b \text{ km s}^{-1}$	74 ± 80
$N(O_{VII}) \text{ cm}^{-2}$	$(2.35 \pm 0.4) \times 10^{16}$
$N(O_{VIII}) \text{ cm}^{-2}$	$(1.81 \pm 0.5) \times 10^{16}$
$N(Ne_{IX}) \text{ cm}^{-2}$	$(7.14 \pm 1.8) \times 10^{15}$

^aassuming $Z = 0.3Z_{\odot}$

Table 5. Baryonic Mass Estimates of the Milky Way

Component	Mass (M_{\odot})
Virial Mass	$1 \times 10^{12} M_{\odot}$
Baryonic Mass ^a	$1.7 \times 10^{11} M_{\odot}$
Stellar + cold gas mass ^b	$6 \times 10^{10} M_{\odot}$
Missing Baryonic Mass	$1.1 \times 10^{11} M_{\odot}$
Measured Hot halo mass	
Average; uniform density (Paper I)	$> 6.1 \times 10^{10} M_{\odot}$
This paper: uniform density	$3.9 \times 10^{10} M_{\odot}$
This paper: β model	$3.2 - 10 \times 10^{10} M_{\odot}$

^aCalculated using cosmological baryon fraction of $f_b = 0.17$ measured by the Wilkinson Microwave Anisotropy Probe (Dunkley et al. 2009)

^b(Sommer-Larsen 2006)

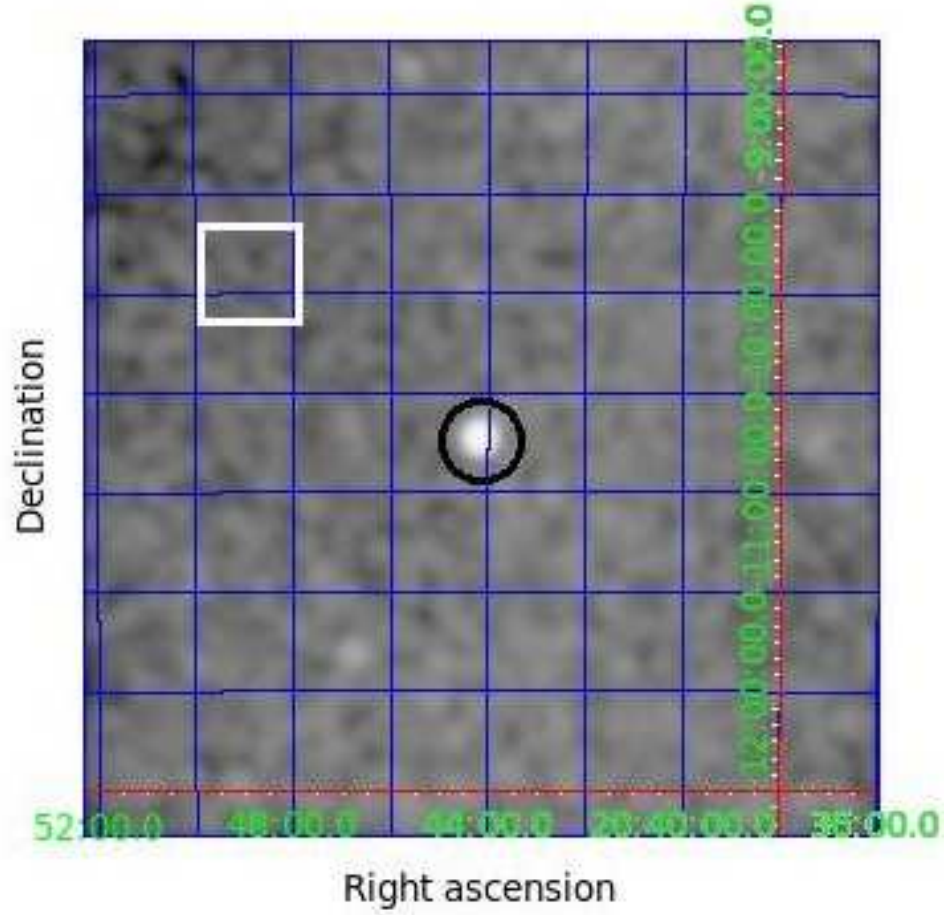


Fig. 1.— RASS 3/4 keV band X-ray map in the vicinity of Mrk 509 (black circle). The white square marks the nearby blank X-ray sky field (*Off-field2*).

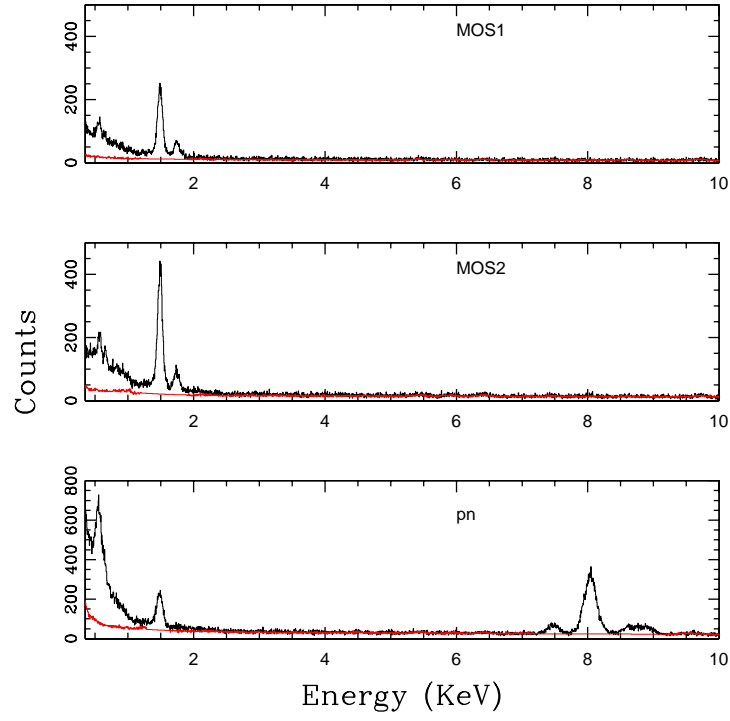


Fig. 2.— XMM-Newton MOS and pn spectra (black curves) of *off-filled2* extracted after removing the point sources. Red curves corresponds to background/QPB spectra.

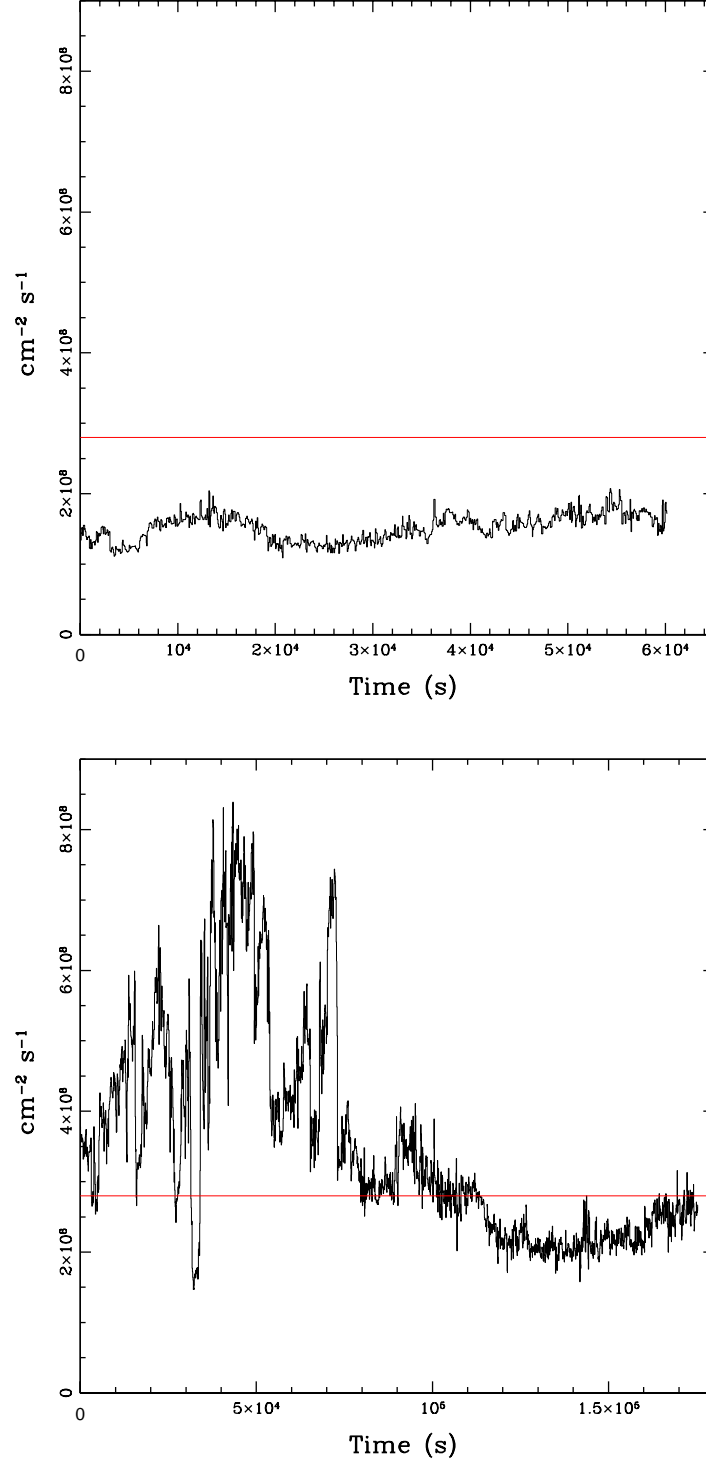


Fig. 3.— Solar wind proton flux data from OMNIWeb during XMM-Newton (top) and Suzaku (bottom) observations of *Off-field2* periods. The *dashed* line shows the average proton flux at 1 AU ($2.8 \times 10^8 \text{ cm}^{-2} \text{s}^{-1}$).

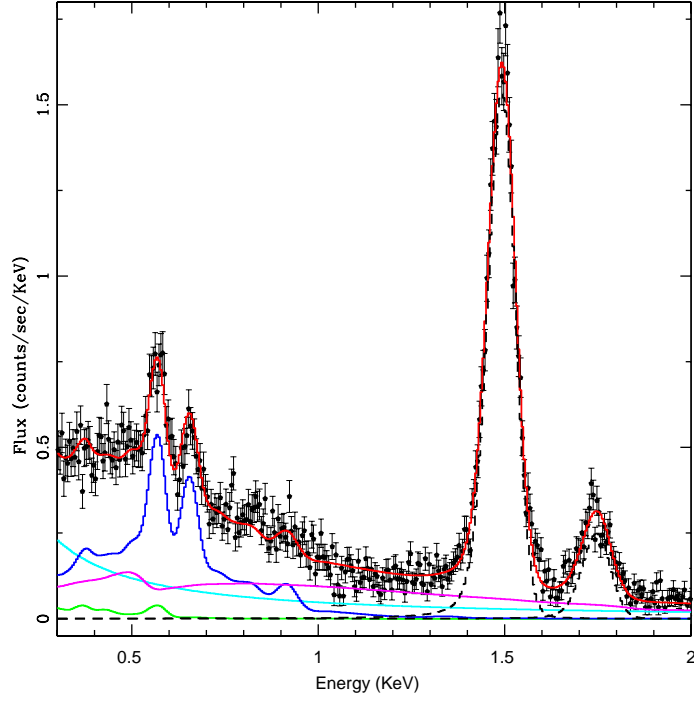


Fig. 4.— MOS2 *Off-field2* spectrum, with the best-fit model ($\chi^2/d.o.f. = 1.1$, red curve). We also plotted the individual components of SDXB: foreground component (LB+SWCX: green curve), extragalactic background (unresolved point sources: magenta curve) and galactic halo (blue curve). The cyan curve corresponds to residual partial background (modeled as unfolded power-law) and the black dashed gaussians model the instrumental Al and Si lines.

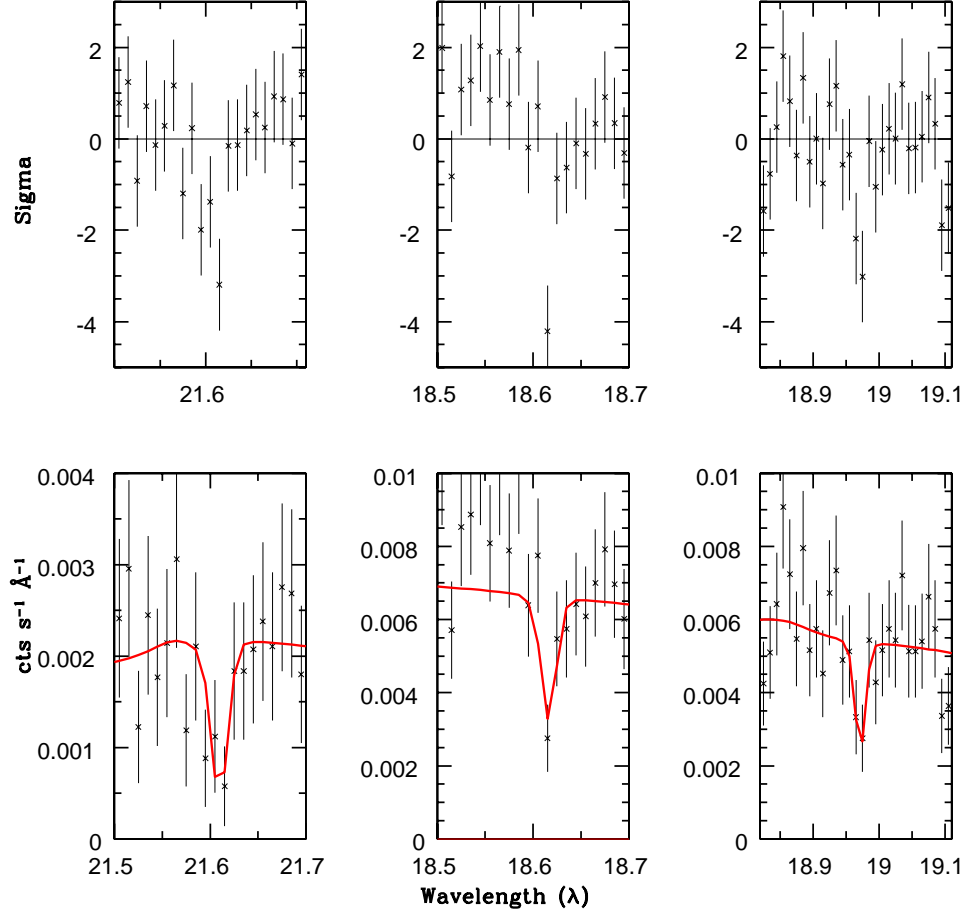


Fig. 5.— Mrk509 Chandra HETG spectrum. O VII $K\alpha$, $K\beta$, and O VIII $K\alpha$ absorption lines are clearly detected and are fitted with gaussian profiles (bottom panel). In the top panel residuals to the continuum model are shown.

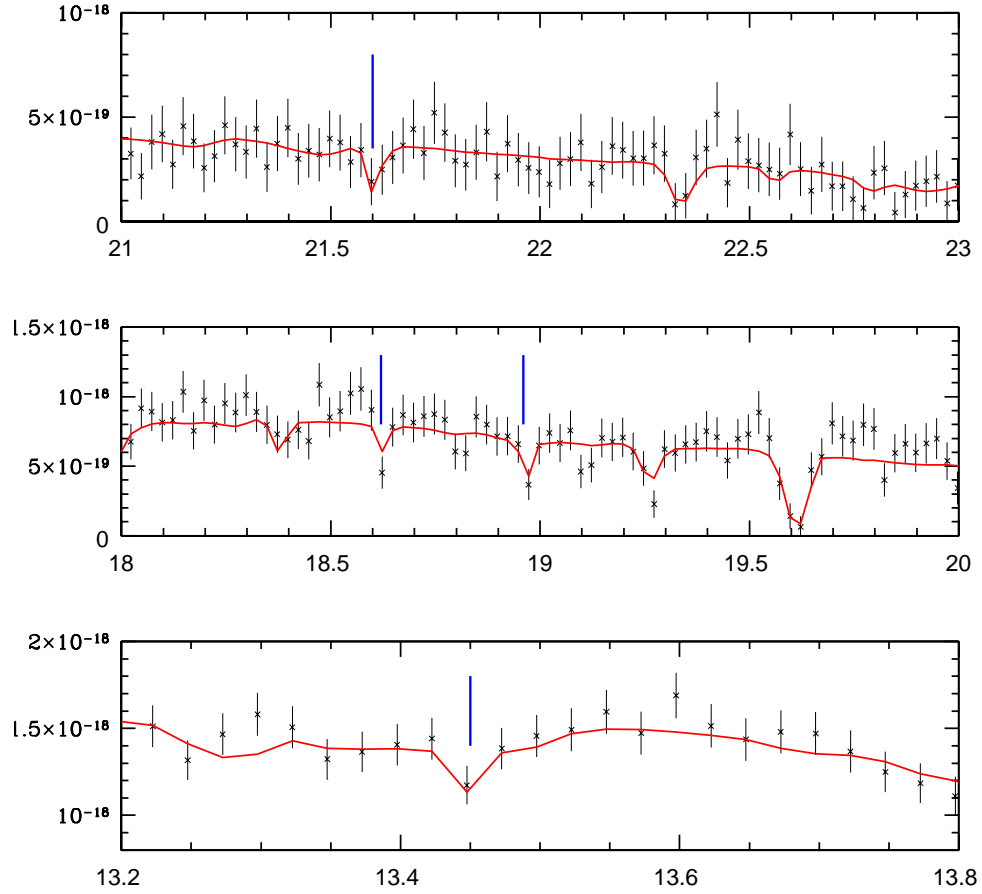


Fig. 6.— PHASE fit to the HETG spectrum of Mrk509. $z = 0$ absorption lines are marked; the rest are from the intrinsic warm absorber.

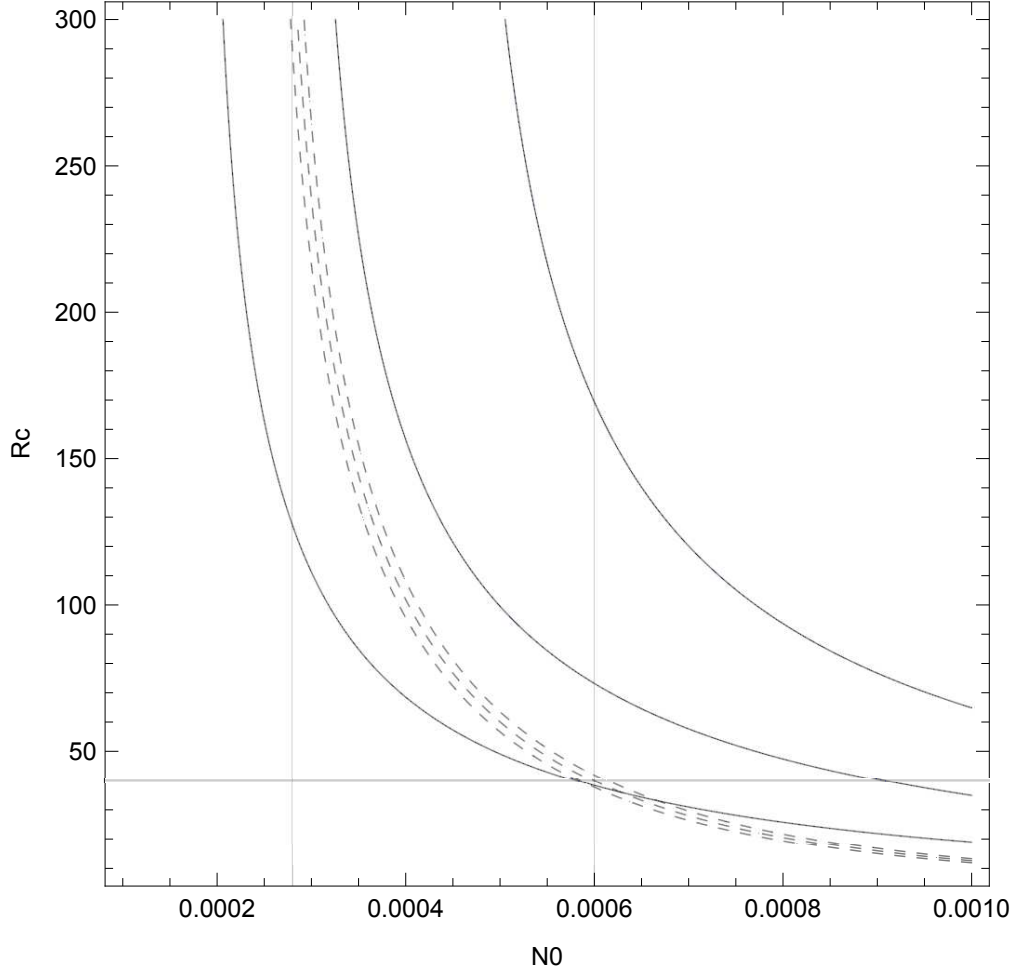


Fig. 7.— A β -model density distribution fit to data. The central density N_0/μ (in cm^{-3}) is plotted on X-axis while the Y-axis plots core radius R_c (in Kpc). The solid lines match the best-fit and 1σ error values of the observed column density. The dashed lines are for the emission measure. Vertical lines show the allowed range in N_0 and the horizontal line shows the lower limit on the core radius.

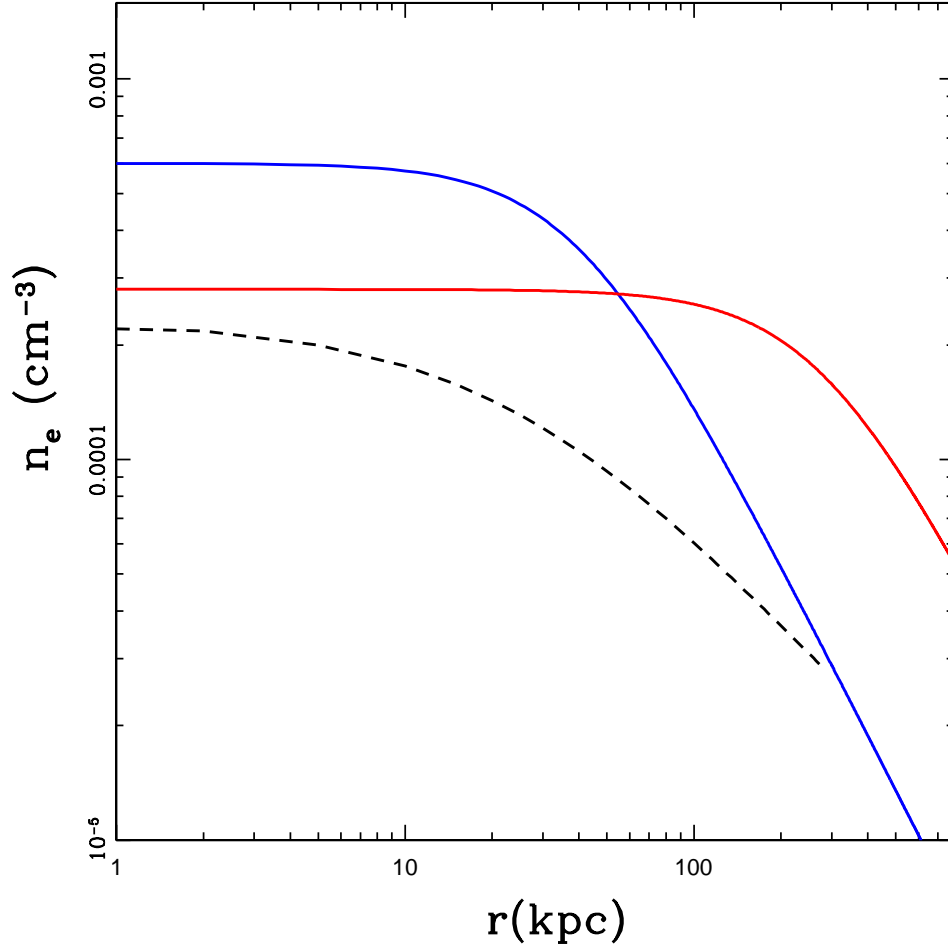


Fig. 8.— The β -profiles deduced from this work are shown with solid lines. The blue and red curves correspond to the upper and lower limits on density, respectively. The dashed black curve is the Maller & Bullock profile from Fang et al. (2013).